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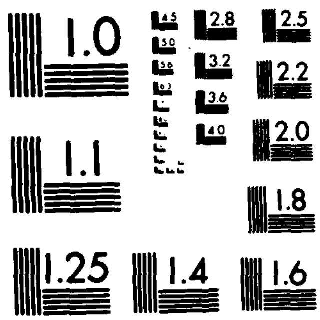

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AIAA-84-0235
An Investigation of Side-Stick Controller/Stability and Control Augmentation System Requirements for Helicopter Terrain Flight Under Reduced Visibility Conditions

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AIAA 22nd Aerospace Sciences Meeting

January 9-12, 1984/Reno, Nevada

AN INVESTIGATION OF SIDE-STICK-CONTROLLER/STABILITY AND CONTROL-AUGMENTATION SYSTEM REQUIREMENTS FOR HELICOPTER TERRAIN FLIGHT UNDER REDUCED VISIBILITY CONDITIONS

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Abstract

A piloted simulator experiment ~~was~~ conducted to evaluate the effects of side-stick-controller characteristics and level of stability and control augmentation on handling qualities for several helicopter, low-altitude flight tasks conducted at night or in adverse weather. These reduced visibility tasks were simulated by providing the pilot with a visually coupled, helmet-mounted display of flight-control symbols superimposed upon terrain-board imagery. Forward-flight, low-speed, and precision-hover control modes were implemented, and a method for ~~the~~ blending of control laws between each control mode was developed. Variations in the level of integration of primary control functions on a single side-stick controller were investigated. For most of the flight tasks investigated, separated controller configurations were preferred to a single, fully integrated side-stick device. Satisfactory handling qualities over all controller configurations were achieved only for a precision-hover task conducted with a high level of stability and control augmentation. Significant degradations in handling qualities occurred for most tasks flown with the helmet-mounted display relative to ~~the~~ identical tasks flown under visual flight conditions.

Introduction

As part of the U.S. Army's Advanced Digital/Optical Control System (ADOCS) program, a series of piloted simulations has been conducted to develop the integrated side-stick-controller characteristics and flight-control laws to be implemented on the ADOCS demonstrator helicopter. This process is providing a significant amount of handling-qualities data applicable to the design of advanced scout/attack rotorcraft which employ integrated controllers.

Two major simulation phases have been completed since January 1981. Phase 1 was conducted at the Boeing Vertol Flight Simulation Facility, which provides a wide-field-of-view visual display and limited six-degree-of-freedom motion cues. This first simulation phase concentrated on the critical low-speed, low-altitude portions of the scout/attack helicopter mission and evaluated tasks under both visual and instrument meteorological conditions (VMC and IMC, respectively).[1] IMC tasks were conducted using a visually coupled helmet-mounted display as the pilot's only source of outside visual cues. A parallel effort was conducted on the six-degree-of-freedom moving-base simulator facilities at Ames Research Center to investigate the effects of reduced levels of stability and control augmentation on handling qualities for helicopter terrain flight under VMC.[2]

During Phase 2, two simulation experiments were performed on the Ames Research Center's Vertical Motion Simulator (VMS) facility which includes a six-degree-of-freedom, large-motion-base simulator and a four-window, computer-generated visual display system. The purpose of the first of these was to evaluate handling qualities under VMC and emphasized tasks that represent elements of the entire scout/attack helicopter mission, including low-speed, transition, and forward flight.[3]

Results from these previous simulations provide information on the interactive effects of side-stick-controller characteristics and level of stability and control augmentation on scout/attack helicopter handling qualities. As reported in Ref. 3, a four-axis, side-stick controller with small deflection in all axes was preferred to either a four-axis, rigid device or one having limited deflection in the pitch and roll axes and no deflection in the vertical and directional axes. However, the preferred four-axis configuration resulted in degraded handling qualities when compared with controller configurations having separated vertical or vertical and directional controllers for certain tasks and for reduced levels of stability and control augmentation. For the VMC flight tasks investigated, satisfactory handling qualities were obtained with blended control laws consisting of the following:

1) Longitudinal: attitude-command/inertial-velocity stabilization for low-speed and attitude-command/airspeed stabilization at high speed

2) Lateral: attitude-command/inertial-velocity stabilization for low-speed and angular-rate-command/attitude stabilization at high speed

3) Directional: yaw-rate-command/heading-hold for low-speed and turn coordination in forward flight

4) Vertical: vertical-velocity-command/altitude-hold

For flight tasks conducted under IMC with the helmet-mounted display, Ref. 1 reports a significant degradation in handling qualities when compared with identical tasks performed under VMC. For the precision-hover tasks investigated, a longitudinal and lateral inertial velocity-command and stabilization system was required to provide satisfactory handling qualities.

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The purpose of the final Phase 2 simulation, the subject of this paper, was to continue the assessment of the interactive effects of side-stick-controller characteristics and vehicle dynamics on handling qualities for a series of demanding tasks, similar to those investigated in Refs. 1 and 3, under reduced visibility conditions using a state-of-the-art night vision aid similar to the one provided in the Phase 1 study. Included in this experiment were investigations of separate forward flight, low-speed, and precision-hover flight-control modes and of the blending of control laws between control modes. Finally, since the previous experiments did not include external disturbances, the effects of wind and turbulence on handling qualities and system performance were assessed for selected evaluation tasks.

Experiment Design

The primary experimental variables selected for investigation were as follows:

1) The pilot's controller configuration: level of integration of control functions on a single side-stick controller

2) Stability and control augmentation system characteristics: level of stabilization and type of response to pilot's control inputs

3) Task demands: hover, low-speed, and forward-flight tasks; transitions from forward flight to hover

Controllers

Various prototype four-axis, side-stick controllers were evaluated in the two previous simulation phases.[1-3] The controllers investigated ranged from no-deflection- (stiff-stick) to large-deflection-type controllers. These simulation studies demonstrated that a four-axis controller with small deflection in all axes was preferred over both a four-axis, stiff-stick design and a design having limited deflection in only the pitch and roll axes. Limited deflection in each control axis improved the pilot's ability to modulate single-axis forces, reduced the tendency for overcontrolling and input coupling, and enhanced control precision for high-gain tasks. Based on the results of these simulation experiments, a four-axis, limited deflection, force controller was fabricated and installed on the evaluation pilot's right side. This controller, manufactured by Lear Siegler, Inc., is a "brassboard" controller similar to the unit that will be used for the ADOCS demonstrator aircraft. The controller is a base-pivot type for pitch and roll inputs; fore-and-aft force produces longitudinal control input, and right-left force produces lateral control input. Yaw control is obtained by twisting about the grip centerline; vertical control is through application of up-down forces. Table 1 presents the force/deflection characteristics of this controller. The Lear Siegler controller was equipped with a grip identical to the one used on controller 3 of Ref. 3. This grip, based on the findings of Ref. 4, was designed to improve the pilot's ability to apply single-axis vertical aand directional control inputs and to minimize interaxis coupling of these inputs.

In addition to investigating the effects of controller force/deflection characteristics, Refs. 1-3 also evaluated the level of integration of controlled axes on a single controller. These research programs showed that for specific tasks, significant improvement in handling qualities could be achieved by separating control of the vertical axis from the remaining three. To allow further investigation of this configuration, a single-axis, limited-deflection controller (controller 2 of Ref. 3) was installed on the pilot's left side. Control of the vertical axis was accomplished through the longitudinal control axis of this controller. To evaluate a more conventional controller arrangement, pedals configured as small-deflection force controllers for directional inputs were installed. Force/deflection characteristics of the collective controller and pedals are shown in Table 2. The three controller configurations (Fig. 1) discussed above provided the desired variation in level of controller integration for this experiment.

Stability and Control Characteristics

Simulation of the baseline flight vehicle was provided by a 10-degree-of-freedom, full-flight envelope generic helicopter mathematical model configured to represent the UH-60A Black Hawk. References 5 and 6 provide a detailed description of the simulation model.

Figure 2 presents a block diagram of the flight-control system design developed for the ADOCS Demonstrator Program. The primary flight-control system (PFCS) was designed to yield satisfactory unaugmented flight by providing feed-forward command augmentation and shaping. The advanced flight-control system (AFCS) included both stabilization feedback loops and a feed-forward control-response model. Stabilization feedback loops were designed solely for maximum gust and upset rejection; no compromise for control response was necessary. Use of a control-response model allowed the shaping of the short- and long-term response to the pilot's control inputs independent of the stabilization level.

Primary flight-control system (PFCS). As indicated in Fig. 3, a pilot force-command signal was provided to each PFCS axis. The signal was shaped, adjusted in gain, passed through a derivative rate-limiter, and fed to the AFCS command model and to the primary UH-60A flight-control system through a feed-forward shaping network. Limiting of the AFCS output was also a function of the PFCS, but was not incorporated for this experiment. The force-command signal quantization, nonlinear command shaping, derivative rate-limiters, and forward path lead-lag shaping are described in detail in Ref. 3.

Advanced flight-control system (AFCS). The attack helicopter mission dictates precise hover control to maintain horizontal position while executing precision hover and bob-up tasks. Accordingly, additional feed-forward and feedback paths were incorporated in the longitudinal and lateral AFCS control laws of Ref. 3 to provide a pilot-selectable hover-hold mode. Figure 4 shows the longitudinal AFCS implemented for this experiment. The lateral axis was implemented in a similar manner. Blending between the hover-hold mode and

other control modes is accomplished by transient-free changes in the structure and gains used in the feed-forward portion of the longitudinal and lateral AFCS control laws. The hover-hold mode provides a velocity-command system with high gain velocity stabilization with or without position feedback. Longitudinal and lateral position reference signals used in the position feedback are derived from groundspeed signals. The hover-hold mode can only be selected if both longitudinal and lateral groundspeeds are less than 5 ft/sec and if the pilot has selected either the hover or bob-up mode of the display symbols. Once selected, the hover-hold mode remains active if longitudinal groundspeed does not exceed 25 ft/sec. With the position-hold enabled, hover-hold logic synchronizes position error to establish a new longitudinal or lateral ground reference position when a nonzero velocity is commanded by the pilot in that axis. Automatic position-relock occurs in each axis when groundspeed in that axis is less than 2 ft/sec.

For forward flight, the same hybrid system for the longitudinal and lateral AFCS was available as that reported in Ref. 3. This hybrid system was implemented to provide automatic blending of control laws as follows:

1) Longitudinal: pitch-attitude-command/groundspeed stabilization for low speed and attitude-command/airspeed stabilization at high speed

2) Roll-attitude-command/groundspeed stabilization for low speed and roll-rate-command/roll-attitude stabilization at high speed

The vertical AFCS implemented for this experiment was a vertical-velocity-command/altitude-hold system. The directional AFCS used was a yaw-rate-command/heading-hold system. Automatic switching above 50 knots between the heading-hold mode and a turn-coordination feature for maneuvering flight was also provided in the directional axis. A detailed description of both vertical and directional AFCS designs is given in Ref. 3.

The generic AFCS variations investigated in this experiment are presented in Table 3. An explanation of the nomenclature used to identify each AFCS configuration follows:

1) Pitch and roll: RA/AT, rate command, attitude stabilization; AT/AT, attitude command, attitude stabilization; AT/LV, attitude command, velocity stabilization; LV/LV, velocity command, velocity stabilization; and LV/PH, velocity command, position hold

2) Yaw: $\dot{\psi}/\psi_H$, yaw-rate command, heading hold

3) Vertical: $\dot{h}/h_H$, vertical velocity command, altitude hold

IMC Display

Since the ADOCS mission is to be flown at night or in adverse weather conditions or both, as well as in VMC, it is necessary to consider not only the effects of the controller and SCAS characteristics, but also the effect on handling qualities of the pilot's night-vision aids. For this experiment, flight under IMC was simulated using the Honeywell Integrated Helmet and Display Sight System (IHADSS). Computer generated symbols, similar to those used in the AH-64 Apache Pilot Night-Vision System (PNVS), were superimposed on a 30° by 40° monochromatic image of the terrain board and presented to the pilot on the helmet-mounted display (HMD) (Fig. 5). This imagery, slaved to the pilot's head movements in azimuth and elevation and driven by aircraft motion parameters, provided the only visual cues available to the evaluation pilot. The pilot's line of sight is tracked with a helmet-mounted sight (HMS) that provides closed-loop command signals to point the terrain-board camera which simulates the turret-mounted night-vision sensor. Since the HMD is coupled to the pilot's head motions, he is able to scan a wide field-of-regard without being constrained to a head-down or look-forward position. Figure 6 shows the HMD and one of the sight-sensing units used to track the head motions, behind the pilot.

Several modifications were made to the display symbols of Ref. 1. These changes, evaluated during preliminary IHADSS checkout testing, were based on pilot commentary elicited in the Ref. 1 simulation program; they include

1) Additional pitch-attitude symbols to provide a more compelling and accurate display of pitch and roll attitude

2) The movement of the heading symbols to the lower center of the display to eliminate the eye muscle strain caused by its usual location well above the display center; the heading scale was also truncated to declutter the display

3) The replacement of the diamond-shaped aircraft nose symbol by a cockpit reference display; this symbol provided information concerning aircraft orientation relative to head azimuth and elevation in a format designed to alleviate the disorientation problems experienced in maneuvering flight reported in Ref. 1

The pilot-selectable display modes, which are used to meet the operational requirements for various attack helicopter mission tasks, are

1) Cruise: high-speed level flight en route to the forward edge of the battle area

2) Transition: low-speed NOE maneuvers, such as dash, quick stop, and sideward flight

3) Hover: stable hover with minimum drift

4) Bob-up: unmask, target acquisition, and remask maneuvers over a selected ground position

Selection of either the hover or bob-up display mode by the pilot is required to engage the hover-hold feature in the longitudinal and lateral AFCS.

Figure 7 presents the display mode symbols divided into two categories, central and peripheral.

Conduct of the Experiment

Facility Description

Ames Research Center's Vertical Motion Simulator (VMS) Facility[7] has a six-degree-of-freedom moving-base cab with 60 ft of available vertical travel (Fig. 8). The simulator cab was modified to include a typical helicopter instrument panel and provisions for mounting the two four-axis, side-stick controllers on the pilot's right and left side (Fig. 9). Adjustable mounting brackets attached to the armrest of each controller allowed orientation of each side-stick controller for comfort and to minimize interaxis control inputs (Fig. 10). In addition to the side-stick controllers, conventional helicopter directional pedals were used as small-displacement force controllers. The visual scene was simulated using a 300:1-scale terrain board and camera visual system depicting both a nap-of-the-Earth (NOE) course (Fig. 11) and an airport runway with evenly spaced obstacles positioned for a slalom course and approach to hover task (Fig. 12). The video signal from this visual system, which simulated the forward-looking infrared (FLIR) sensor signal, was mixed optically with the computer-generated symbols and presented to the pilot on the HMD.

Evaluation Tasks

Evaluation of the various controller/SCAS combinations under reduced visibility conditions using the IHADSS was accomplished for four low-speed and hover tasks: NOE, precision hover, and bob-up (Fig. 13), and a 30-knot slalom; one high-speed maneuvering task, a 90-knot slalom (Fig. 14); and two transition tasks, a straight-in approach to hover and a turning approach to hover (Fig. 15). A two-pilot situation was simulated; that is, no secondary tasks (e.g., armament, communication, or navigation system management) were required of the pilot during the evaluations. These tasks were identical to the ones performed in the two previous ADOCS simulations[1,3] in order to provide a basis for comparison between the results of this experiment and the results of the previous experiments. The precision-hover and bob-up tasks were evaluated under a specified level of wind and turbulence to evaluate the effects on system and pilot performance. The precision-hover task was performed both with and without a 20-knot headwind, and the bob-up task was evaluated both with and without a wind shear of 6 knots at 20 ft increasing to 50 knots at 200 ft. The vertical turbulence intensity simulated for both tasks was 10% of the mean wind speed measured at 20 ft above ground level (AGL), and the horizontal turbulence intensity was 20% of the mean wind speed measured at 20 ft AGL. This low-altitude turbulence model is described in detail in Ref. 8.

<u>NOE</u>. This multiaxis control task required the pilot to fly through three legs of a narrow canyon (125 ft wide and 50 ft high) having two sharp turns (70° left and 80° right) and two obstacles (50 ft high), to reach a termination hover area. During the first leg of the course, an acceleration to 50 knots was performed before crossing a road, followed by a deceleration to 25 knots while maintaining a lateral ground track and an altitude of 30 ft. After executing a coordinated left turn to enter the second leg, the pilot was required to climb to fly over an obstacle and remask to 30 ft in as short a time as possible while attempting to maintain an airspeed of 25 knots. Following a sharp right turn, the pilot flew over a second obstacle, restored altitude to 30 ft, and decelerated to a hover point in the termination area.

<u>Precision hover</u>. This task required the pilot to descend from a 30-ft altitude to a 5-ft hover height while aligning the helicopter with a rock located in the center of the bob-up area. A precision hover was maintained using the rock as a reference point.

<u>Bob-up</u>. This multiaxis task consisted of a vertical unmask maneuver from 25 ft to 100 ft, a heading turn to acquire a target, and a vertical remask to the original hover height. The pilot was required to hold a fixed horizontal ground position throughout the vertical unmask/remask and heading-turn maneuvers.

<u>Slalom</u>. This task emphasized low or high-speed lateral avoidance, and required the pilot to maneuver around 50-ft-high obstacles evenly spaced (spacing determined by airspeed) on the runway centerline while maintaining altitude (30 ft AGL), and a specific lateral ground track determined by runway width and obstacle separation.

<u>Straight-in approach to hover</u>. This task started with the helicopter in level flight at 100 knots and at 275 ft AGL. The pilot was required to descend and decelerate on a 4° glide slope over a horizontal distance of 4000 ft to a 25-ft hover point in front of a 50-ft obstacle.

<u>Turning approach to hover</u>. This task also emphasized forward flight to low-speed transition, and required the pilot to perform a left or right descending, decelerating turn from 100 knots and 200 ft AGL and arrive at a 25-ft hover in front of a 50-ft obstacle on the runway centerline.

Evaluation Pilots' Background and Experience

Three experimental test pilots participated as evaluation pilots in this simulation study — one each from Boeing-Vertol, NASA, and the U.S. Army. A summary of their flight time and related experience in side-stick controller and IHADSS development is presented in Table 4. Two of the evaluation pilots (B and C) participated in the two previous ADOCS simulation studies.[1,3] Pilot A was the primary evaluator for this experiment. A total of 54 simulation flight hours and 890 evaluation data runs were accumulated.

Data Collection and Analysis

Both pilot evaluation data and quantitative system performance data were collected. The pilot evaluation data consist of Cooper-Harper handling-qualities ratings[9] and pilot commentary. At the end of each evaluation run the pilot assigned a single numerical Cooper-Harper rating to the particular controller/AFCS/task combination under investigation. In addition, the pilot was asked to provide commentary to help identify those aspects of the system that most heavily influenced the rating. Experimental results presented herein are based on an analysis of pilot ratings and comments. The results are summarized using averaged pilot ratings to illustrate general trends. The quantitative system performance data

consist of magnetic tape recordings of specified flight parameters and statistical data, which include mean and standard deviations of helicopter flight parameters relative to a reference hover position or desired flightpath. These statistical data will be used as a measure of system performance.

Other Experimental Considerations

A significant amount of simulation time was allotted for pilot familiarization with the IHADSS equipment and modified display symbols. In order to minimize pilot learning-curve effects, IMC evaluation data were not collected until the pilots demonstrated a consistent level of proficiency with IHADSS.

Generally, only one task was performed by the pilot in a typical simulation session. Changes to the controller configuration were made during a session only after investigating a full spectrum of AFCS characteristics for that particular configuration. Before each evaluation run, the pilots were told the controller configuration and command response type for each control axis. They were not informed of the stabilization level in each axis. For the low-speed tasks, the pilots were given time to feel out the system before each data run, and, for the high-speed and transition tasks, they were allowed to take a practice run, if desired.

Results

This simulator investigation was designed to study the interactive effects of controller configuration, longitudinal and lateral AFCS type, and task demands on the handling qualities of the ADOCS aircraft under night and adverse weather flight conditions. The effect of wind shear and turbulence on the pilots' performance of the bob-up and precision hover tasks was also investigated.

IMC/VMC Comparison

Flight under IMC with the IHADSS had a significant effect on pilot ratings for the low-speed NOE maneuvering task. Figure 16 compares VMC data from a previous simulation[3] and IMC data obtained during this simulation for the same NOE task. Combinations of three controller configurations and three AFCS types are compared. Average IMC pilot ratings were degraded approximately 1.5 points relative to the VMC ratings for all AFCS and controller combinations evaluated. Satisfactory handling qualities were achieved under VMC with an attitude-command system, whereas handling qualities degraded to only adequate with the same AFCS configuration for the IMC task.

Figure 17 presents a comparison of VMC and IMC ratings for all tasks evaluated during this simulation. The VMC data are again from Ref. 3, and the IMC data were generated during the subject simulation phase. Data shown are Cooper-Harper ratings averaged over all controller configurations and AFCS types evaluated for each task. As seen in Fig. 17, the average rating did not vary significantly as a function of VMC task. However, task variation had a larger effect on pilot rating for flight under IMC with the IHADSS. The largest degradation in IMC pilot ratings occurred for the NOE task. More pilot head motion was required for low-speed maneuvering tasks such as the NOE, 30-knot slalom, and turning approach-to-hover tasks. Pilot comments indicate that the rapid head movement required to monitor aircraft position and ground track caused disorientation and increased workload. For tasks in which little or no head motion is required, such as the precision hover and slalom at high speed (90 knots), IMC ratings approached those for the same tasks conducted under VMC.

Controller/AFCS Configuration Comparisons

All tasks were evaluated with the three selected controller configurations to assess the effects of side-stick-controller integration level on handling qualities under IMC with the IHADSS. The effect of various types of AFCS on these results was also investigated.

Transition tasks. Controller configuration had a significant effect on pilot ratings for the approach-to-hover tasks, as presented in Fig. 18. Separated controllers – (3 + 1)collective and (2 + 1 + 1) configurations – improved pilot ratings by 1.0 to 1.5 pilot rating points compared with the four-axis controller configuration. Pilots had more difficulty with the four-axis controller during the transition tasks because of the requirement to hold forces in the vertical axis while modulating pitch and roll control. Transfer of vertical control from the right-hand four-axis controller to a single-axis left-hand side-stick eliminated this control problem and improved pilot ratings appreciably, as shown in Fig. 18; similar trends in pilot rating occurred in an investigation of the identical tasks conducted in VMC.[3]

Both the attitude-command/attitude-stabilization (AT/AT) and the hybrid AFCS were favored over the rate-command/attitude-stabilization (RA/AT) system for the approach-to-hover tasks, with satisfactory ratings achieved for the straight and right-turning approach-to-hover.

Slalom task. In both the 30- and 90-knot slalom tasks, the pilots preferred separated controllers [i.e., (3 + 1)collective and (2 + 1 + 1)], as shown in Fig. 19. The pilot's ability to maintain a constant airspeed and altitude was a primary measure of performance for these tasks. Pilot comments indicate that more cross-coupling occurred with the four-axis controller and resulted in significant airspeed and altitude deviations. Overall, for both slalom tasks, the (2 + 1 + 1) configuration received the best pilot ratings. Pilots' comments suggest that there was more tendency to couple roll inputs into yaw with the (4 + 0) and (3 + 1)collective configurations. The (2 + 1 + 1) configuration eliminated roll/yaw interaxis control coupling for this task.

For the 30-knot slalom task, the AT/LV system received the best ratings. This system was preferred over the RA/AT or the AT/AT system because of improved groundspeed hold during maneuvering. In the 90-knot slalom, the AFCS had less of an effect on pilot ratings.

NOE task. The NOE task flown under IMC was found to be the most difficult and demanding task for the evaluation pilots to perform. The IHADSS display provides a limited instantaneous

field-of-view image and gives minimal rate-of-closure cues to the pilot, thereby making this task extremely difficult to perform with low levels of stability and control augmentation. Even for the highest level of augmentation evaluated for this task, the AT/LV system, satisfactory ratings were not achieved for the NOE task under IMC (Fig. 20). The pitch-attitude- and roll-attitude-command systems (AT/AT and AT/LV) improved pilot ratings approximately 2.0 points compared with a rate-command system (RA/AT). The RA/AT system received marginally adequate ratings from 6.0 to 6.5.

Controller configuration did not have a significant effect on pilot ratings for the NOE task. Collective-control inputs were required only for single-axis vertical maneuvering over the berms. Providing vertical control from a separate left-hand controller did not have a noticeable effect on pilot rating for this task. Figure 20 shows that the four-axis controller achieved pilot ratings comparable to the (3 + 1)collective and (2 + 1 + 1) configurations for the NOE task.

Precision hover/bob-up tasks. Additional levels of stability and control augmentation were evaluated for the precision hover and bob-up tasks and compared with the previously described systems evaluated for the low-speed maneuvering tasks: the NOE and slalom tasks. Two velocity-command systems were included in the matrix of test configurations: one having outer-loop groundspeed stabilization (LV/LV) and the other incorporating a position-hold feature (LV/PH).

Pilot ratings for the precision hover task under wind and turbulence conditions (Fig. 21) were improved with a velocity-command system (LV/LV) compared with an attitude-command system (AT/LV). Satisfactory ratings were obtained with all controller configurations evaluated, and the velocity-command/position-hold (LV/PH) system received the best ratings, approximately 2.5 on the Cooper-Harper scale. Little preference for a particular controller configuration was noticed for this task. The precision hover task required high-frequency pilot control using primarily single-axis inputs. Cross-axis control coupling was not a major problem for this task.

The ability to maintain horizontal ground position was used by the pilots as a measure of performance for the bob-up task. This information was displayed to the pilot by the bob-up mode symbols of the IHADSS display. The velocity-command system (LV/LV) resulted in improved pilot ratings for all controller configurations, as shown in Fig. 22. With the position-hold mode engaged (LV/PH), pilot ratings of 3.5 were obtained for all controller configurations under the simulated wind, shear, and turbulence conditions. In general, the four-axis controller exhibited degraded pilot ratings for the bob-up task compared with the (3 + 1)collective and (2 + 1 + 1) configurations. There was more tendency for cross-axis control coupling with a four-axis controller under both calm and turbulent wind conditions.

Most data collected for the bob-up and precision hover tasks were obtained under conditions of wind shear and moderate turbulence; initial baseline data were gathered in calm air for comparison. Figures 21 and 22 show the effect of wind shear and turbulence for both the bob-up and precision hover tasks. Pilot ratings were degraded approximately 1.5 points under turbulence and wind shear conditions.

The effect of turbulence on bob-up task performance is presented in Fig. 23. Deviations in longitudinal and lateral position from the desired hover location are used to calculate a mean radius, the radius of a circle containing one-half the total number of data points. For a lower level of stability and control augmentation, mean radius is significantly greater with turbulence compared with calm-air conditions. Even though the pilots' ratings for the IMC bob-up task were degraded, their performance under IMC was better than VMC performance. This outcome is due to the lack of strong visual position cues in the simulation under VMC, particularly at the higher altitudes reached during the bob-up maneuver, and to the additional guidance for maintaining a precision hover provided to the pilot under IMC by the IHADSS display symbols.

AFCS Summary

As indicated in Fig. 24, satisfactory pilot ratings were achieved consistently only under IMC with the LV/PH system for the precision-hover and bob-up tasks. Although receiving, on the average, only adequate ratings, the hybrid longitudinal and lateral AFCS was preferred for the IMC maneuvering tasks over all AFCS configurations investigated. The longitudinal and lateral RA/AT system yielded both marginally adequate handling qualities, when averaged over all tasks and controller configurations, and the widest dispersion of pilot ratings.

Conclusions

The effects of variations in side-stick-controller configurations and stability and control augmentation characteristics on scout/attack helicopter handling qualities were evaluated using the Ames Research Center Vertical Motion Simulator. Various tasks, each typical of a segment of a scout/attack helicopter mission, were evaluated under instrument meteorological conditions (IMC) using a visually coupled helmet-mounted display. Conclusions from this experiment are summarized below.

Controller Configuration

The controller configurations that provided separate control of the vertical or vertical and directional axis achieved either comparable or improved pilot ratings compared with ratings given to the four-axis controller, dependent on the particular task under evaluation. Separated controller configurations provided the following significant advantages for IMC terrain flight:

1) Elimination of unintentional cross-axis coupling, especially vertical-to-pitch/roll coupling

2) Reduction of pilot workload for multiaxis tasks, for example, by the separation of any required steady vertical or directional control forces from continuously modulated pitch and roll forces

AFCS Configurations

A comparison of various generic longitudinal and lateral advanced flight control systems (AFCS) was performed. The directional and vertical axes were augmented to achieve heading-hold/turn-coordination and vertical-velocity-command/altitude-hold, respectively. Satisfactory handling qualities were not achieved for any combination of controller and AFCS investigated for the low-speed IMC maneuvering tasks. Satisfactory ratings were obtained under IMC for both the bob-up and precision hover tasks when performed in calm air with a longitudinal and lateral velocity-command/stabilization system. With wind and turbulence, the addition of a position-hold feature was required to maintain satisfactory ratings for the bob-up task.

IMC Display Effects

The reduction in quality of visual cues and occasional disorientation experienced when looking off the aircraft centerline with the visually coupled helmet-mounted display caused significant degradations in handling qualities for certain IMC tasks relative to the identical tasks conducted under VMC. This degradation was especially severe for a low-speed NOE maneuvering task which required a significant amount of pilot head motion to acquire the required visual information. Significant improvements in hover-position-hold performance occurred for the IMC tasks compared with the VMC tasks because of the pilots' use of the displayed superimposed symbols which included explicit inertial velocity and position error information.

Acknowledgments

The experiment described in this paper was conducted by Boeing Vertol Company for the Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories (AVSCOM) under NASA Ames Research Center contract NAS2-10880, as part of the Army's Advanced Digital/Optical Control System program, managed by the Applied Technology Laboratory, Ft. Eustis, Va. The authors are grateful to the following pilots for their participation: L. Freisner (Boeing Vertol), M. Morgan (NAE, Canada), P. Morris (U.S. Army-Ames Research Center), G. Tucker (Ames Research Center), and J. Tulloch (Boeing Vertol).

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[8]Aiken, E. W., "A Mathematical Representation of an Advanced Helicopter for Piloted Simulator Investigations of Control System and Display Variations," USAAVRADCOM TR80-4-2 (NASA TM-81203), July 1980.

[9]Cooper, G. E. and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, 1969.

Table 1 Four-axis controller force/deflection characteristics

Axis	Gradient	Maximum deflection	Maximum force	Breakout
Longitudinal	2.09 lb/deg	±7.6° or ±0.8 in. at 6-in. radius	±15.9 lb	0.0 lb
Lateral	1.67 lb/deg	±7.6° or ±0.8 in. at 6-in. radius	±12.8 lb	0.0 lb
Directional	5.0 in.-lb/deg	±7.0°	±35 in.-lb	0.0 lb
Vertical	95 lb/in. (up) 85 lb/in. (down)	±0.156 in.	15.82 lb (up) 13.86 lb (down)	1.0 lb (up) 0.6 lb (down)

Table 2 Alternative controller force/deflection characteristics

Controller	Gradient	Maximum deflection	Maximum force	Breakout
Single-axis collective (left-hand)	1.82 lb/deg	±8.3°	±16.0 lb	±0.5 lb
Pedals	40.0 lb/in.	±0.78 in.	±45.0 lb	±6.0 lb

Table 3 Generic AFCS configuration matrix

	Stabilization level							
Response command model	Longitudinal/lateral				Directional		Vertical	
	RA	AT	LV	PH	RA	AT	LV	LP
AC	○				○	○	NA	NA
RA	○	●	○		○	●	NA	NA
AT		●	●				NA	NA
LA					NA	NA	○	○
LV			●	●	NA	NA	○	●

● Configurations evaluated in current and previous experiments.
○ Configurations evaluated in previous experiments.

	Pitch/roll	Yaw	Vertical
Angular acceleration	AC	$\ddot{\psi}$	--
Angular rate	RA	$\dot{\psi}$	--
Angular attitude	AT	ψ	--
Linear acceleration	LA	--	$\ddot{h}$
Linear velocity	LV	--	$\dot{h}$
Linear position	LP or PH	--	h_H

Table 4 Summary of pilot experience

Pilot	Affiliation	Flight time, hr		Related experience			
				Side-stick controller development		IHADSS development	
		Helicopter/ fixed-wing	Total	Flight test	Simulation	Flight test	Simulation
A	Boeing-Vertol	5000 (H) 1000 (F)	6000	X	X	--	--
B	NASA Ames	2745 (H) 1200 (F)	3945	X	X	X	X
C	U.S. Army	1065 (H) 2520 (F)	3585	--	X	X	X

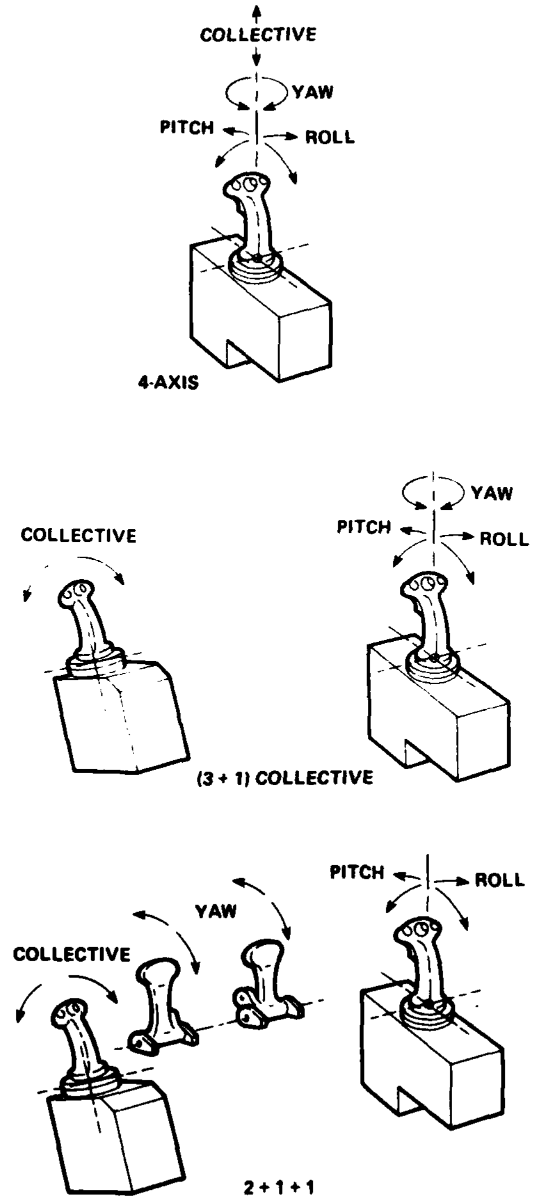


Fig. 1 Controller configurations.

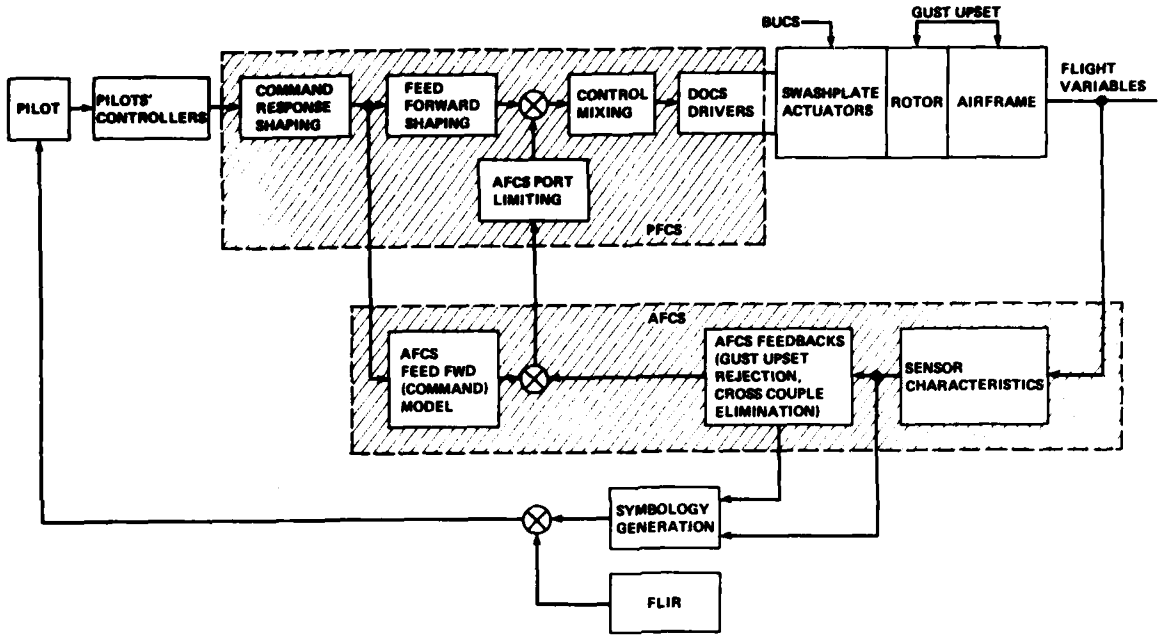


Fig. 2 ADOCS demonstrator flight-control system.

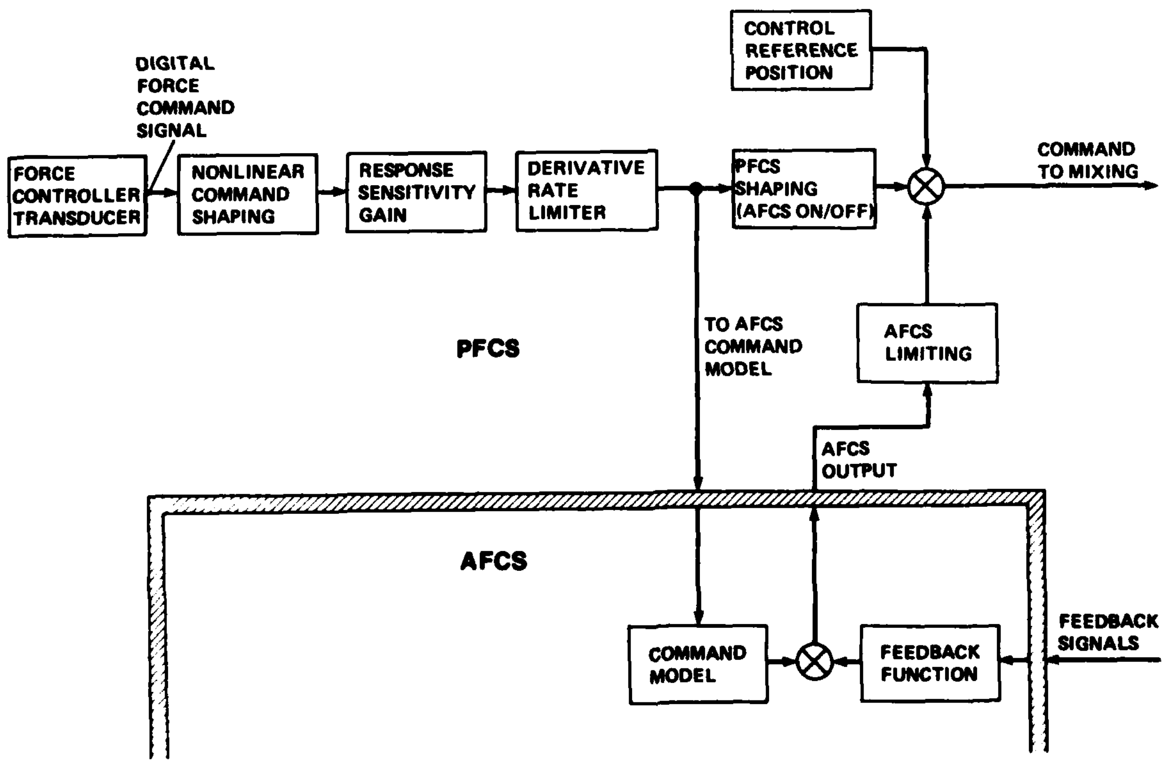


Fig. 3 Primary flight-control system.

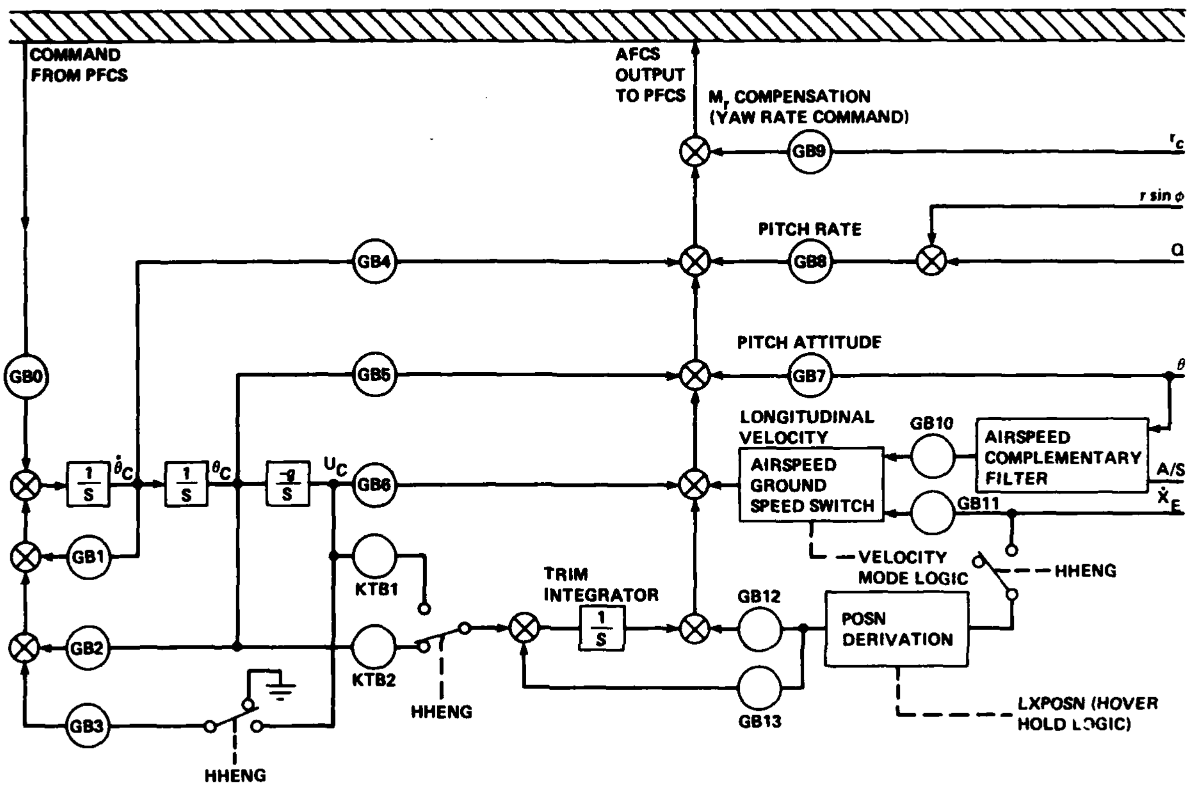
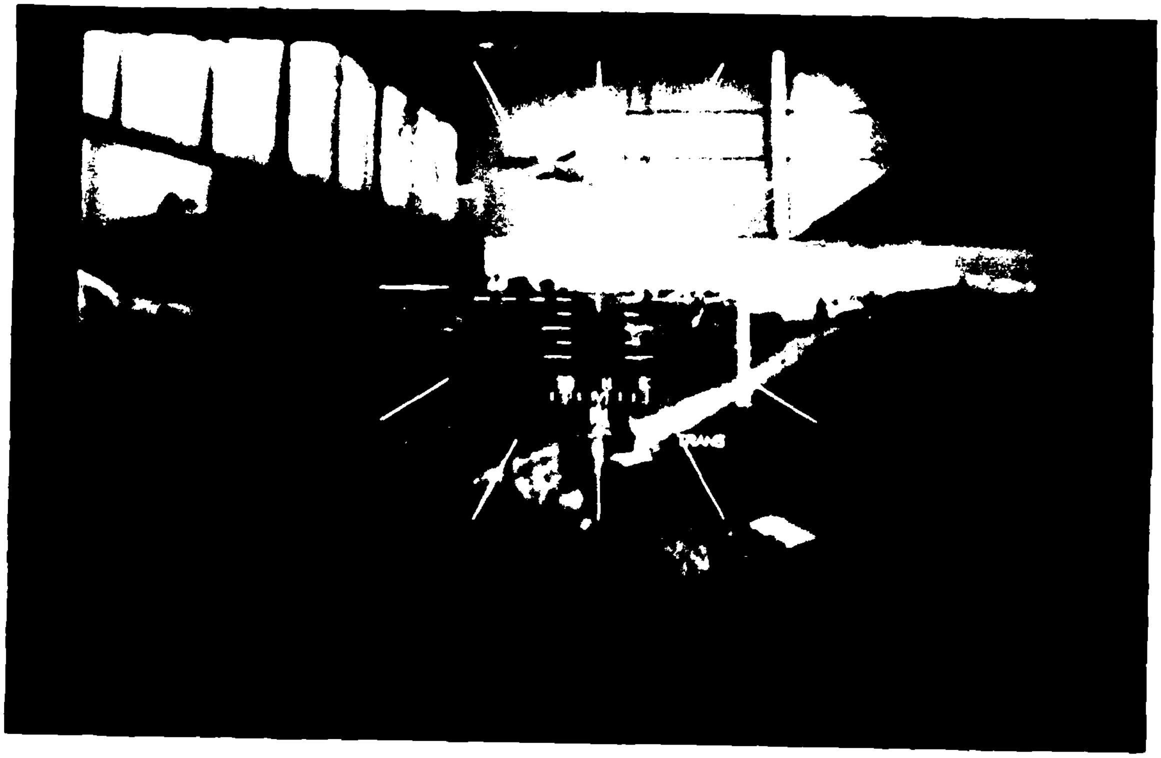
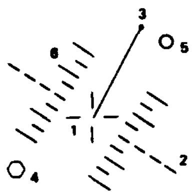


Fig. 4 Advanced flight-control system: longitudinal axis.

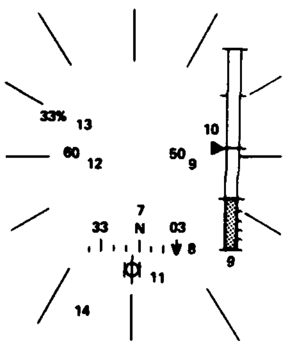


[illegible]

Fig. 6 Integrated helmet and display sight system installation.



CENTRAL SYMBOL	INFORMATION	MODES		
		CRUISE/ TRANS	HOVER	BOB UP
1. AIRCRAFT REFERENCE	FIXED REFERENCE FOR HORIZON LINE VELOCITY VECTOR, HOVER POSITION, CYCLIC DIRECTOR, AND FIRE CONTROL SYMBOLS	X	X	X
2. HORIZON LINE	PITCH AND ROLL ATTITUDE WITH RESPECT TO AIRCRAFT REFERENCE (INDICATING NO PITCH AND LEFT ROLL)	X	X	X
3. VELOCITY VECTOR	HORIZONTAL DOPPLER VELOCITY COMPONENTS (INDICATING FORWARD AND RIGHT DRIFT VELOCITIES). SENSITIVITY VARIES WITH MODE	X	X	X
4. HOVER POSITION	DESIGNATED HOVER POSITION WITH RESPECT TO AIRCRAFT REFERENCE SYMBOL (INDICATING AIRCRAFT FORWARD AND TO RIGHT OF DESIRED HOVER POSITION)		X	X
5. CYCLIC DIRECTOR (ACCELERATION CUE)	CYCLIC STICK COMMAND WITH RESPECT TO HOVER POSITION SYMBOL (INDICATING LEFT AND AFT CYCLIC STICK REQUIRED TO RETURN TO DESIGNATED HOVER POSITION). APPROXIMATED BY WASHED OUT PITCH/ROLL ATTITUDE		X	X
6. PITCH ATTITUDE	PITCH ATTITUDE WITH RESPECT TO AIRCRAFT REFERENCE. EACH LINE REPRESENTS A CHANGE OF 5° (POSITIVE UP, NEGATIVE DOWN)	X	X	X



PERIPHERAL SYMBOL	INFORMATION	MODES		
		CRUISE/ TRANS	HOVER	BOB UP
7. AIRCRAFT HEADING	MOVING TAPE INDICATION OF HEADING (INDICATING NORTH)	X	X	X
8. HEADING ERROR	HEADING AT TIME BOB UP MODE SELECTED (INDICATING 030)			X
9. RADAR ALTITUDE	HEIGHT ABOVE GROUND LEVEL IN BOTH ANALOG AND DIGITAL FORM (INDICATING 50 ft)	X	X	X
10. RATE OF CLIMB	MOVING POINTER WITH FULL SCALE DEFLECTION OF 1,000 ft/min (INDICATING 0 ft/min)	X	X	X
11. LATERAL ACCELERATION	INCLINOMETER INDICATION OF SIDE FORCE	X	X	X
12. AIRSPEED	DIGITAL READOUT, knots	X	X	X
13. TORQUE	ENGINE TORQUE, percent	X	X	X
14. COCKPIT REFERENCE SYMBOL	PILOT'S HEAD POSITION WITH RESPECT TO THE COCKPIT REFERENCE SYSTEM	X	X	X

Fig. 7 Display mode symbols.

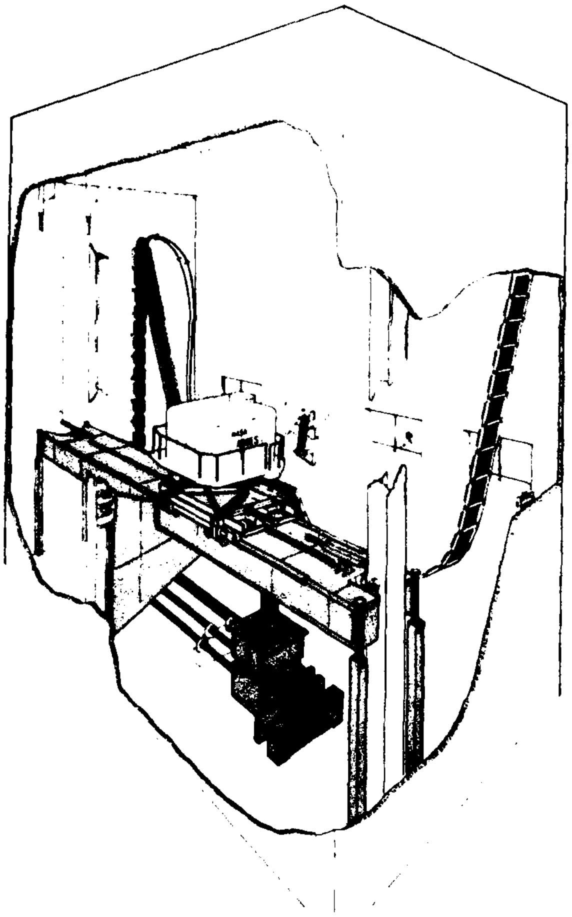


Fig. 8 NASA Ames Vertical Motion Simulator (VMS).

Fig. 9 Simulator cockpit and controller installation.

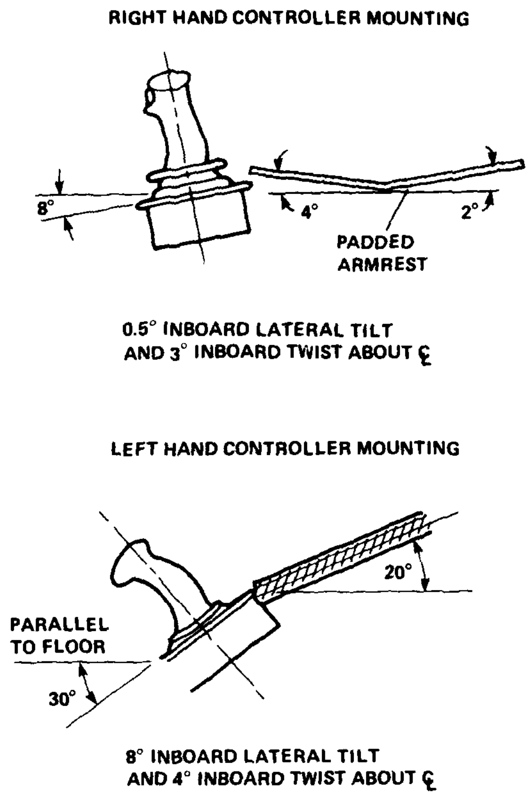


Fig. 10 Controller mounting.

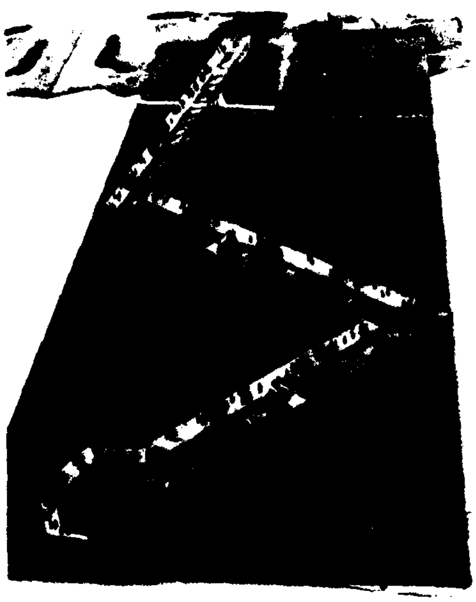


Fig. 11 Nap-of-the-Earth course.

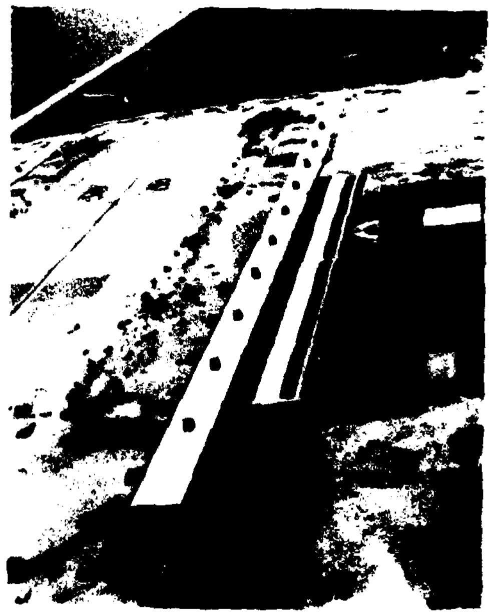


Fig. 12 Slalom course.

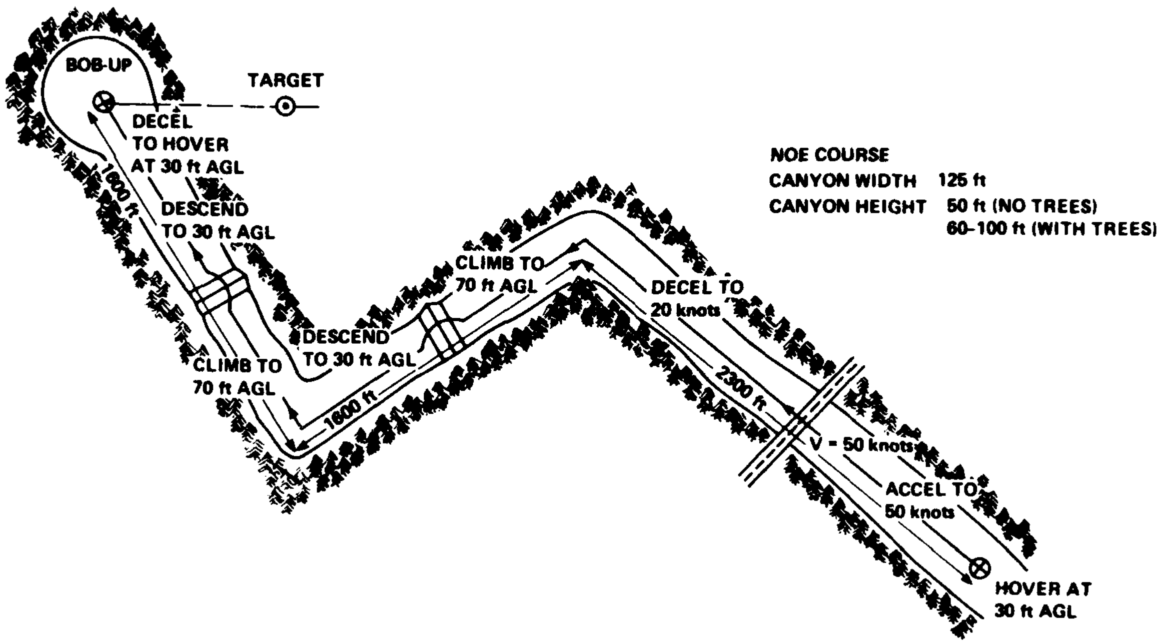


Fig. 13 Low-speed evaluation tasks: NOE, precision hover, and bob-up.

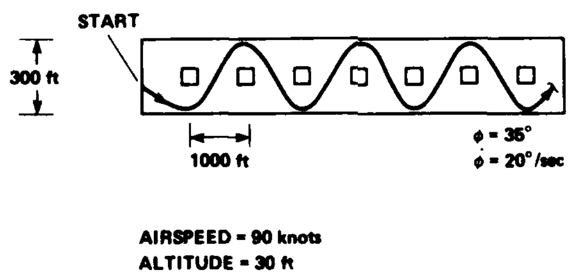
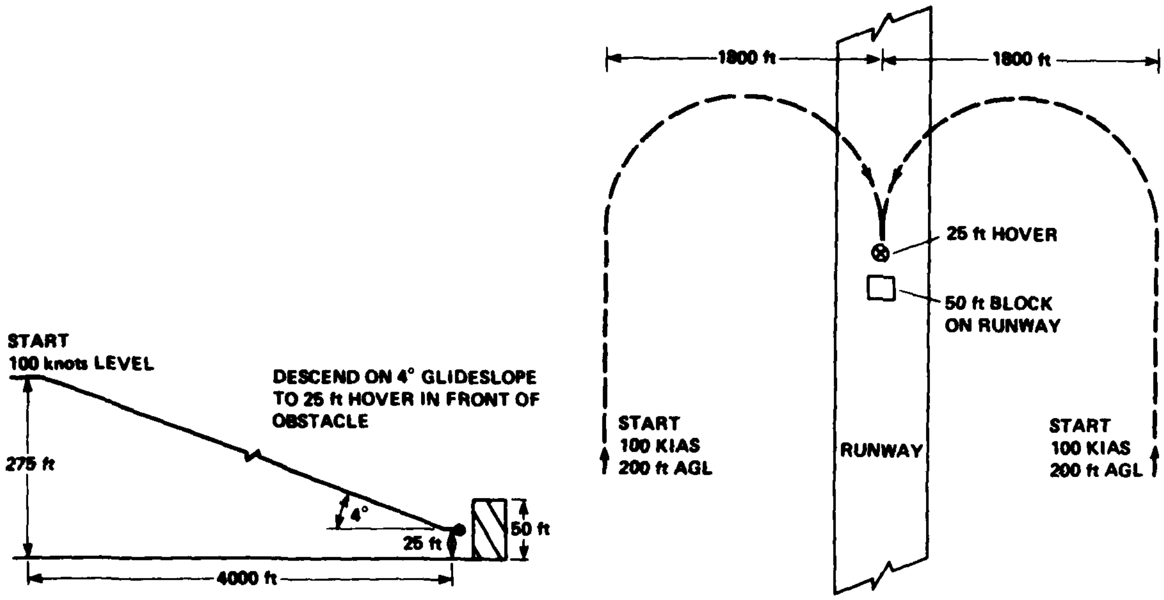


Fig. 14 High-speed slalom task.



a) Straight-in approach to hover.

b) Turning approach to hover.

Fig. 15 Transition evaluation tasks.

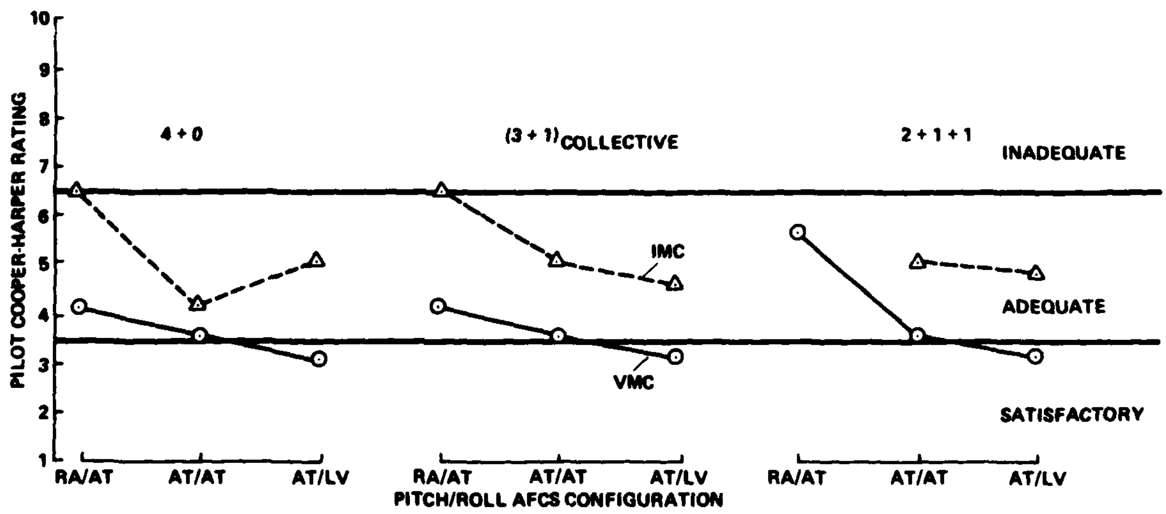


Fig. 16 Comparison of IMC and VMC pilot ratings: NOE task.

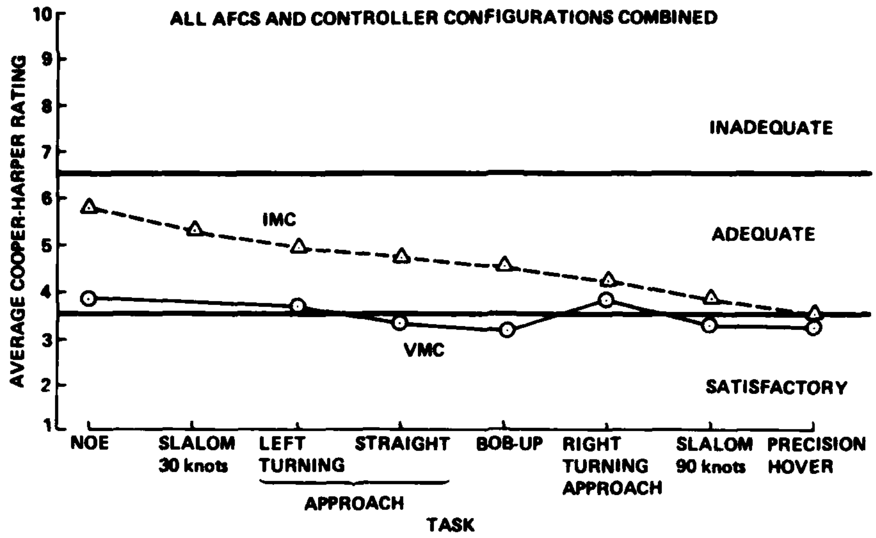


Fig. 17 Effect of task on pilot ratings.

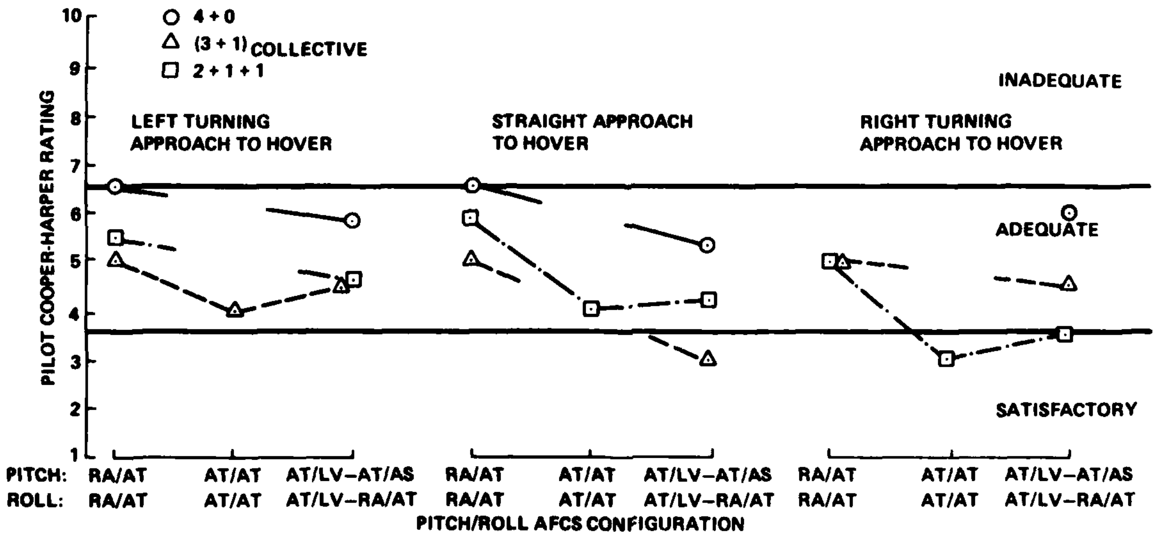


Fig. 18 Pilot ratings for approach to hover tasks: IMC.

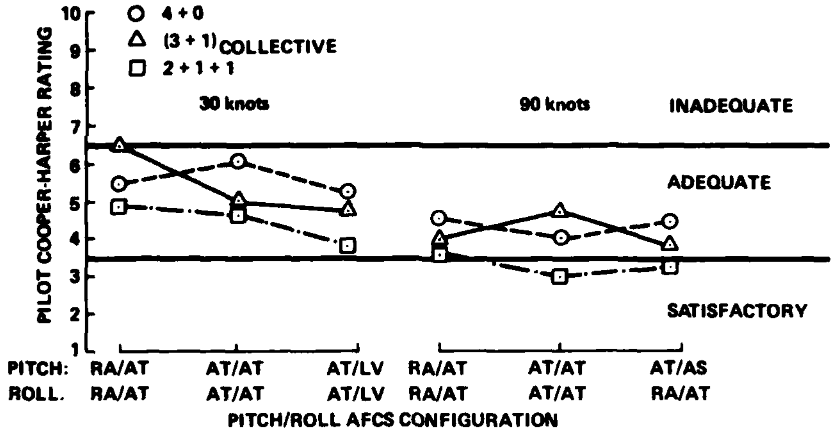


Fig. 19 Pilot ratings for slalom task: IMC.

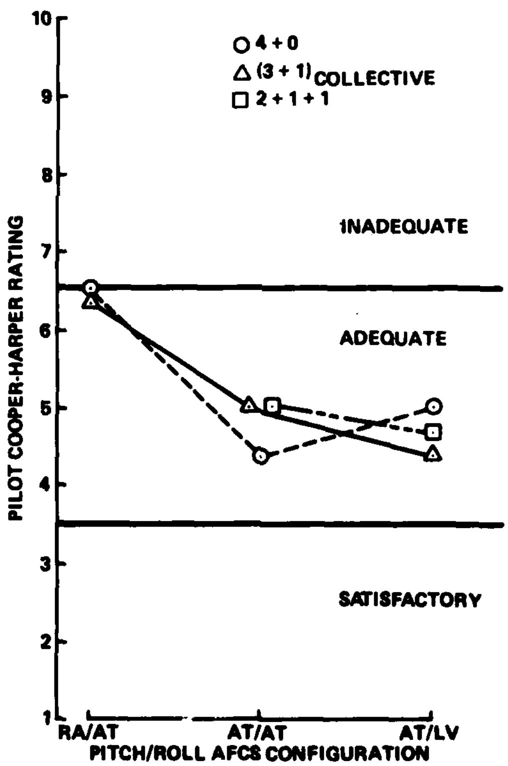


Fig. 20 Pilot ratings for NOE task: IMC.

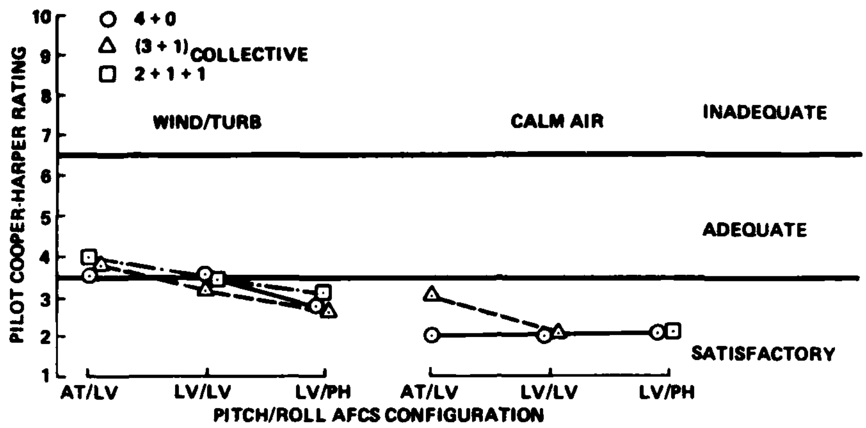


Fig. 21 Pilot ratings for precision hover task: IMC.

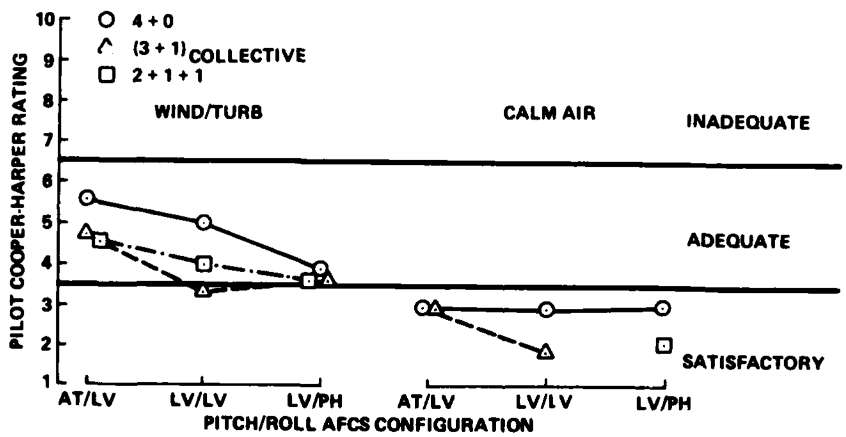


Fig. 22 Pilot ratings for bob-up task: IMC.

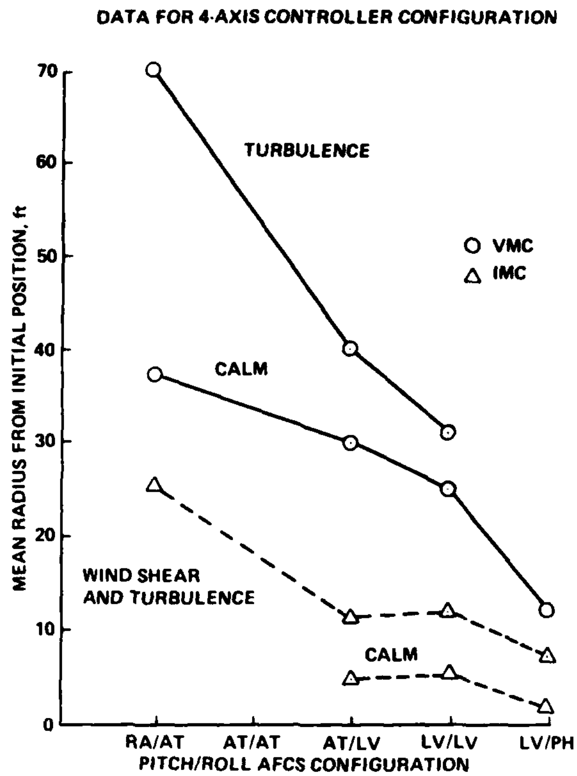


Fig. 23 Effect of turbulence on bob-up performance: IMC and VMC.

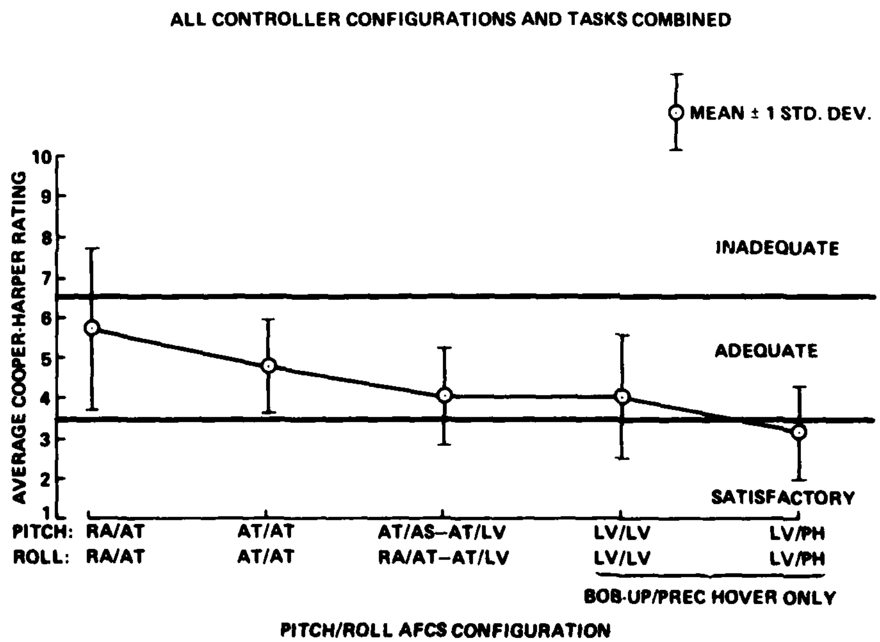


Fig. 24 Effect of AFCS on pilot ratings: IMC.

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